



LUND UNIVERSITY

Role of the Δ Resonance in the Population of a Four-Nucleon State in the $^{56}\text{Fe} \rightarrow ^{54}\text{Fe}$ Reaction at Relativistic Energies

Podolyák, Zs; Shand, C. M.; Lalovic, Natasa; Gerl, J.; Rudolph, D.; Alexander, T.; Boutachkov, P.; Cortés, M. L.; Górska, M.; Kojouharov, I.; Kurz, N.; Louchart, C.; Merchán, E.; Michelagnoli, C.; Pérez-Vidal, R. M.; Pietri, S.; Ralet, D.; Reese, M.; Schaffner, H.; Stahl, Ch; Weick, H.; Ameil, F.; De Angelis, G.; Arici, T.; Carroll, R.; Dombrádi, Zs; Gadea, A.; Golubev, P.; Lettmann, M.; Lizarazo, C.; Mahboub, D.; Pai, H.; Patel, Z.; Pietralla, N.; Regan, P. H.; Sarmiento, L. G.; Wieland, O.; Wilson, E.; Birkenbach, B.; Bruyneel, B.; Burrows, I.; Charles, L.; Clément, E.; Crespi, F. C L; Cullen, D. M.; Désesquelles, P.; Eberth, J.; González, V.; Habermann, T.; Harkness-Brennan, L.

Published in:
Physical Review Letters

DOI:
[10.1103/PhysRevLett.117.222302](https://doi.org/10.1103/PhysRevLett.117.222302)

2016

Document Version:
Publisher's PDF, also known as Version of record

[Link to publication](#)

Citation for published version (APA):
Podolyák, Z., Shand, C. M., Lalovic, N., Gerl, J., Rudolph, D., Alexander, T., Boutachkov, P., Cortés, M. L., Górska, M., Kojouharov, I., Kurz, N., Louchart, C., Merchán, E., Michelagnoli, C., Pérez-Vidal, R. M., Pietri, S., Ralet, D., Reese, M., Schaffner, H., ... Valiente Dóbon, J. J. (2016). Role of the Δ Resonance in the Population of a Four-Nucleon State in the $^{56}\text{Fe} \rightarrow ^{54}\text{Fe}$ Reaction at Relativistic Energies. *Physical Review Letters*, 117(22), Article 222302. <https://doi.org/10.1103/PhysRevLett.117.222302>

Total number of authors:
65

Creative Commons License:
Unspecified

General rights

Unless other specific re-use rights are stated the following general rights apply:
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: <https://creativecommons.org/licenses/>

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 17. May. 2025

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Role of the Δ Resonance in the Population of a Four-Nucleon State in the $^{56}\text{Fe} \rightarrow ^{54}\text{Fe}$ Reaction at Relativistic Energies

Zs. Podolyák,¹ C. M. Shand,¹ N. Lalović,^{2,3} J. Gerl,³ D. Rudolph,² T. Alexander,¹ P. Boutachkov,³ M. L. Cortés,^{3,4} M. Górska,³ I. Kojouharov,³ N. Kurz,³ C. Louchart,⁴ E. Merchán,⁴ C. Michelagnoli,⁵ R. M. Pérez-Vidal,⁶ S. Pietri,³ D. Ralet,^{4,3} M. Reese,⁴ H. Schaffner,³ Ch. Stahl,⁴ H. Weick,³ F. Ameil,³ G. de Angelis,⁷ T. Arici,^{3,8} R. Carroll,¹ Zs. Dombrádi,⁹ A. Gadea,⁶ P. Golubev,² M. Lettmann,⁴ C. Lizarazo,^{4,3} D. Mahboub,¹⁰ H. Pai,⁴ Z. Patel,¹ N. Pietralla,⁴ P. H. Regan,¹ L. G. Sarmiento,² O. Wieland,¹¹ E. Wilson,¹ B. Birkenbach,¹² B. Bruyneel,¹³ I. Burrows,¹⁴ L. Charles,¹⁵ E. Clément,⁵ F. C. L. Crespi,^{16,11} D. M. Cullen,¹⁷ P. Désesquelles,¹⁸ J. Eberth,¹² V. González,¹⁹ T. Habermann,^{4,3} L. Harkness-Brennan,²⁰ H. Hess,¹² D. S. Judson,²⁰ A. Jungclaus,²¹ W. Korten,¹³ M. Labiche,¹⁴ A. Maj,²² D. Mengoni,^{23,24} D. R. Napoli,⁷ A. Pullia,^{16,11} B. Quintana,²⁵ G. Rainovski,²⁶ P. Reiter,¹² M. D. Salsac,¹³ E. Sanchis,¹⁹ and J. J. Valiente Dóbon⁷

¹Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom

²Department of Physics, Lund University, S-22100 Lund, Sweden

³GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany

⁴Institut für Kernphysik, TU Darmstadt, D-64289 Darmstadt, Germany

⁵GANIL, CEA/DRF-CNRS/IN2P3, F-14076 Caen Cedex 05, France

⁶Instituto de Física Corpuscular, Universitat de Valencia, E-46980 Valencia, Spain

⁷INFN, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy

⁸Justus-Liebig-Universität Giessen, D-35392 Giessen, Germany

⁹Institute for Nuclear Research, Hungarian Academy of Sciences, P.O. Box 51, Debrecen H-4001, Hungary

¹⁰Physics Department, University of Hail, PO Box 2440 Hail, Saudi Arabia

¹¹INFN, Sezione di Milano, I-20133 Milano, Italy

¹²Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany

¹³Irfu, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

¹⁴STFC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom

¹⁵Institut Pluridisciplinaire Hubert Curien, CNRS-IN2P3, Université de Strasbourg, F-67037 Strasbourg, France

¹⁶Dipartimento di Fisica dell'Università degli Studi di Milano, I-20133 Milano, Italy

¹⁷School of Physics and Astronomy, Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom

¹⁸Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse—CSNSM, CNRS/IN2P3 and University Paris-Sud, F-91405 Orsay Campus, France

¹⁹Department of Electronic Engineering, University of Valencia, E-46100 Burjassot (Valencia), Spain

²⁰Oliver Lodge Laboratory, The University of Liverpool, Liverpool L69 7ZE, United Kingdom

²¹Instituto de Estructura de la Materia, CSIC, Madrid, E-28006 Madrid, Spain

²²Institute of Nuclear Physics Polish Academy of Sciences, PL-31-342 Krakow, Poland

²³Dipartimento di Fisica e Astronomia dell'Università degli Studi di Padova, I-35131 Padova, Italy

²⁴INFN, Sezione di Padova, I-35131 Padova, Italy

²⁵Laboratorio de Radiaciones Ionizantes, Universidad de Salamanca, E-37008 Salamanca, Spain

²⁶Faculty of Physics, St. Kliment Ohridski University of Sofia, 1164 Sofia, Bulgaria

(Received 2 June 2016; revised manuscript received 14 September 2016; published 23 November 2016)

The ^{54}Fe nucleus was populated from a ^{56}Fe beam impinging on a Be target with an energy of $E/A = 500$ MeV. The internal decay via γ -ray emission of the 10^+ metastable state was observed. As the structure of this isomeric state has to involve at least four unpaired nucleons, it cannot be populated in a simple two-neutron removal reaction from the ^{56}Fe ground state. The isomeric state was produced in the low-momentum (-energy) tail of the parallel momentum (energy) distribution of ^{54}Fe , suggesting that it was populated via the decay of the Δ^0 resonance into a proton. This process allows the population of four-nucleon states, such as the observed isomer. Therefore, it is concluded that the observation of this 10^+ metastable state in ^{54}Fe is a consequence of the quark structure of the nucleons.

DOI: 10.1103/PhysRevLett.117.222302

Introduction.—The structure of atomic nuclei can be understood considering the interaction between its constituents, protons and neutrons. The properties of nuclear states, being of single-particle or collective type, are always

expressed in terms of proton and neutron excitations. Although nucleons are not elementary particles, their inner structure usually does not have to be considered in order to explain the low-energy nuclear properties. One exception is

the magnetic moment of the nucleus, where the nonzero value in the case of the neutron [1] and the unexpectedly large value for proton [2] provided early evidence that nucleons are composite, not elementary particles.

The nucleons, protons and neutrons consist of three quarks [3,4]. The lowest energy excitation of a nucleon is the Δ resonance at an energy of 1232 MeV [5]. The Δ resonance of a proton, Δ^+ , can decay into a proton ($\Delta^+ \rightarrow \pi^0 + p$), or into a neutron ($\Delta^+ \rightarrow \pi^+ + n$). Similarly, the Δ resonance of a neutron, Δ^0 , can decay into a neutron ($\Delta^0 \rightarrow \pi^0 + n$), or into a proton ($\Delta^0 \rightarrow \pi^- + p$). The fact that the Δ resonance plays a role in relativistic energy charge-exchange reactions was established, by studying the final ejectile nuclei in the 1980s [6].

Here we present results of an experiment where the population of an *excited state* of a nucleus is the consequence of the inner quark structure of the nucleon. The nucleus of interest was populated in relativistic energy heavy-ion collision.

Understanding relativistic energy reactions [7] is in itself important for several reasons. It forms the basis of existing and future radioactive-beam facilities [8,9], as it is one of the main processes to produce previously unidentified nuclear species [10]. It is also the mechanism which explains the nucleosynthesis of the chemical elements beryllium, boron, and possibly lithium [11]. These elements are not produced in the stars, but from the fragmentation of carbon and oxygen in the interstellar medium.

We define relativistic energy reactions, those which occur during the collision between two nuclei at relative velocities higher than the Fermi velocity of the nucleons ($v_F \sim 10^6$ m/s). Peripheral collisions, resulting in fragments with masses close to those of the projectile and target, can be described rather successfully by the two-step abrasion-ablation model [12,13]. The macroscopic abrasion model, the most successful so far, relies on the concept of a clean cut of the projectile nucleus by the target (and vice versa). According to the model, since the relative velocity of the reaction partners is much higher than v_F , the nucleon-nucleon collisions are restricted to the overlap zone. The parts of the nuclei outside the overlap zone, called spectators or prefragments, are not supposed to be affected in the abrasion process. Considering nucleons as elementary particles, as in both abrasion and ablation phases nucleons are removed, the reaction products will always have fewer or an equal number of protons and neutrons than the initial nucleus. Therefore, the product will be a fragment of the initial nucleus. Accordingly, we adopt the term fragmentation for this process in the present Letter. We include in this term direct processes such as one or multinucleon removals (sometimes called cold fragmentation).

The existence of metastable (isomeric) states in nuclei allows for a very sensitive study of the reaction products and thus the reaction process itself. The fragments can be

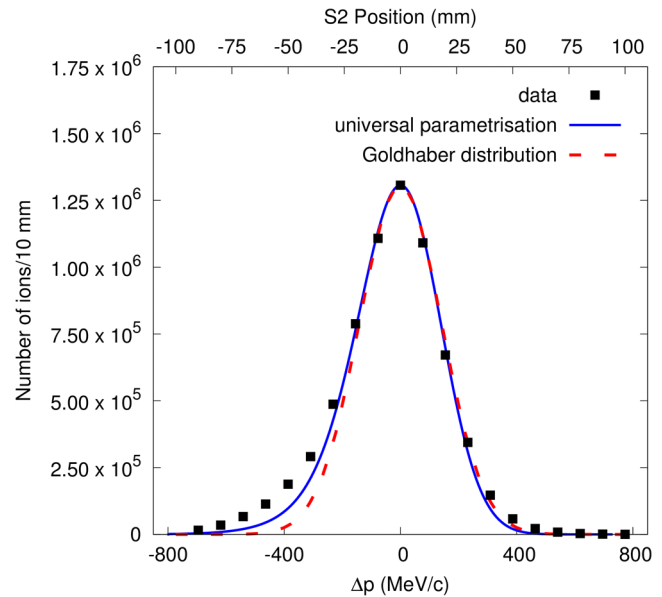


FIG. 1. Parallel momentum distribution of the ^{54}Fe ions, as deduced from the position measurement (upper X axis) at the intermediate focal plane of the fragment separator. The measured distribution is compared with the universal parametrization of [22] (continuous line) and a symmetric distribution as given by the Goldhaber formula [23] (dashed line).

separated and identified, and their decays investigated in essentially background free conditions. The technique is often used to gain access to the structure of exotic nuclei [14–16], as well as for angular momentum population studies [17]. Here we will use isomeric decays in a novel way, namely, to disentangle different contributions to the mechanism of relativistic heavy-ion collisions. The influence of nucleonic excitation on the population of excited states is suggested.

Experimental details.—A primary ^{56}Fe beam at an energy of $E/A = 500$ MeV was provided by the SIS-18 accelerator at GSI, Darmstadt, Germany. The ^{56}Fe ions impinged on a 662 mg/cm^2 ^9Be target. The reaction products of interest were selected and identified in flight on an event-by-event basis by the fragment separator (FRS) [18]. The FRS was optimized for the transmission of bare ^{54}Fe ions. The identification of the fragments was done by magnetic rigidity and energy loss measurements [19]. The transmitted and identified ions were slowed down in a variable thickness aluminum degrader and finally implanted in a passive plastic stopper. A total of 6.8×10^6 ^{54}Fe nuclei were identified. The delayed γ rays correlated with the implanted ions were detected with the advanced gamma tracking array (AGATA) [20]. The stopper was positioned 15 cm downstream from the nominal center of AGATA in order to increase detection efficiency [21].

The use of the thin production target ensured that the energy straggling in the target is minimal and, consequently, the momentum distribution of the fragments is

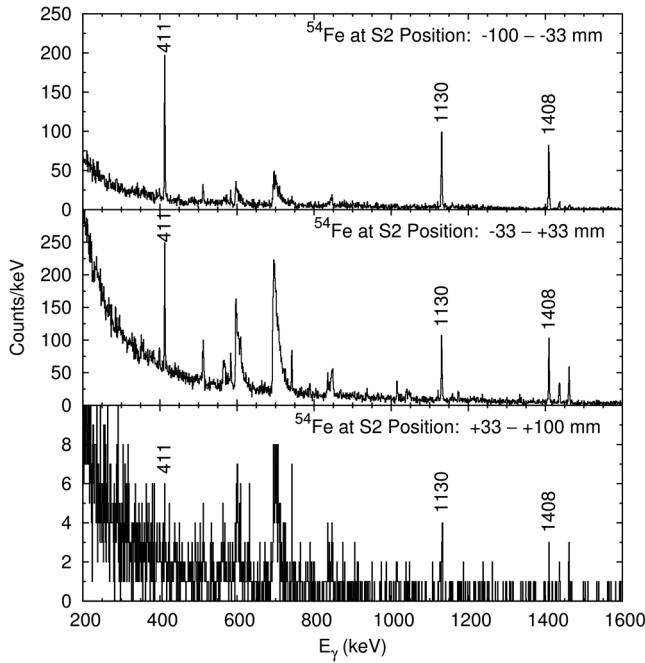


FIG. 2. Delayed ($\Delta t = 117\text{--}1960$ ns) γ -ray spectrum associated with ^{54}Fe . The three panels correspond to ^{54}Fe ions with different parallel momentum ranges. (top) $\Delta p = -750, -247$ MeV/c (9.8×10^5 ^{54}Fe ions); (middle) $\Delta p = -247, +247$ MeV/c (55.8×10^5 ions); (bottom) $\Delta p = +247, +750$ MeV/c (1.64×10^5 ions).

determined by the reaction mechanism. The FRS was operated in achromatic mode with open slits, resulting in 100% optical transmission for the centred ^{54}Fe ions.

Results.—The parallel momentum distribution of fragments can be deduced from their magnetic rigidity, that is from their physical distribution at the dispersive focal plane at the middle of the fragment separator. The parallel momentum distribution of the ^{54}Fe fragments is shown in Fig. 1.

The delayed γ -ray spectrum associated with ^{54}Fe is shown in Fig. 2. Several γ rays are observed, which originate from the decay of the well known $T_{1/2} = 364(7)$ ns $I^\pi = 10^+$ isomeric (metastable) state [24,25].

The isomeric ratio, IR, is defined as the probability that in the reaction a nucleus is produced in an isomeric state. It can be determined experimentally as $\text{IR} = Y/N_{\text{imp}}FG$, where N_{imp} is the number of implanted ions, and Y is the isomeric yield. F and G are correction factors for the in-flight isomer decay losses and the finite detection time of the γ radiation, respectively. The isomeric yield is given by $Y = N_\gamma/\epsilon_{\text{eff}}b_\gamma$, where N_γ is the number of counts in the γ -ray line depopulating the isomer, b_γ is the absolute γ -ray branching ratio, and ϵ_{eff} is the γ -ray detection efficiency. For more details see, e.g., Ref. [19].

The isomeric ratio of the 10^+ isomer in ^{54}Fe was determined as a weighted average from the γ rays at 411, 1130, 1408, and 3431 keV. Its overall value is quite

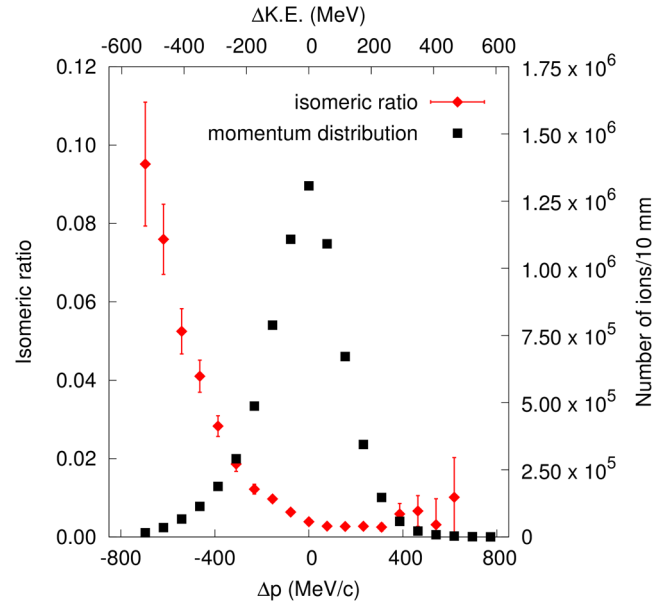


FIG. 3. Isomeric ratio of the 10^+ isomeric state in ^{54}Fe as a function of momentum transfer and corresponding kinetic energy loss (upper X axis). The measured parallel momentum distribution of the ^{54}Fe ions is also shown.

small at 0.77(6)%. Its dependence on the transferred momentum in the reaction is shown in Fig. 3. To investigate its momentum dependence, only the statistical errors on N_γ are shown. The systematic errors, dominated by the absolute efficiency and the loss of ^{54}Fe ions after identification due to reactions (estimated to be 20%), are around 10%, and affect all data points in the same way. The isomeric ratio is close to zero in the center of the distribution and at positive momentum transfer to the fragment. However, it is sizable, in the order of several percent, at negative momentum transfer. The isomeric ratio increases with the amount of transferred parallel momentum.

Discussion.—In relativistic energy fragmentation the parallel momentum distribution is well understood, and it is determined by the removed nucleons. In the case of two particle removal, its width is connected to the angular momentum of the removed nucleon pair [26]. At high bombarding energies, such as in the present case, it is expected to be symmetrical [27,28] around the zero momentum transfer. At lower energies there is a low momentum tail, understood as a contribution from deep-inelastic reactions. The size of the tail is dependent on the bombarding energy and it is larger at lower energies. The momentum distribution can be reproduced with the so called “universal parametrization,” using parameters obtained from experiments [22].

As Fig. 1 shows, the experimental distribution measured here for ^{54}Fe is close to symmetric, but there is an additional contribution, a tail, at negative momentum transfer. The tail is rather large for $E/A = 500$ MeV bombarding energy. The aforementioned universal parametrization predicts a very small tail, and so it is not able

to reproduce the measured momentum distribution (see Fig. 1).

In fragmentation reactions, by removing two neutrons from the primary ^{56}Fe beam, only two-neutron states can be populated in ^{54}Fe . This is always the case, independently of whether it is a direct two-neutron removal reaction or a neutron removal followed by the evaporation of a neutron, or even two consequent reactions in the thin target ($\sim 0.5\%$ of the events). The ground state of ^{56}Fe has zero angular momentum (spin). However, the valence space does not contain enough angular momentum for two holes to create a state with spin $I = 10\hbar$. Modern shell-model calculations include the full pf shell, accounting for protons and neutrons up to $N = Z = 40$. Therefore, the maximum spin of two-neutron states is $I^\pi = 6^+$ from the $\nu f_{7/2}^{-2}$ two-hole configuration. $I^\pi = 10^+$ can be obtained first with two neutrons in the $\nu h_{11/2}$ orbital. This is in the upper part of the $N = 50\text{--}82$ shell, and it is expected to be essentially empty. The $h_{11/2}^2$ component of the isomer can be estimated from the proton decay of the analog 10^+ state in the mirror nucleus ^{54}Ni , and it is in the order of 10^{-6} [29]. Consequently, they play no significant role in the structure of the 10^+ isomer, and the production of this state requires at least four unpaired particles [29]. Therefore, it cannot be populated by fragmentation of ^{56}Fe . The mechanism of populating the 10^+ isomer in ^{54}Fe from ^{56}Fe at relativistic energies has to be more complex.

The fragmentation and additional components of the relativistic energy reaction reaction can be disentangled by considering that fragmentation has essentially a symmetric momentum distribution. The momentum distribution of ^{54}Fe nuclei produced in additional reactions is shown in Fig. 4. It was obtained by subtracting the distribution of the universal parametrization (shown in Fig. 1) from the measured distribution. The large error bars are related to the uncertainty on where the middle of the measured distribution really is. An uncertainty of 1 mm was considered. As only the additional, nonfragmentation, reactions can produce the 10^+ isomer, the isomeric ratio is recalculated, and it is given on the same figure.

The nonfragmentation events show a maximum, at around momentum transfer $\Delta p \sim -400$ MeV/ c , corresponding to ~ -300 MeV kinetic energy shift. The isomeric ratio increases at high momentum transfer. At the low momentum transfer side, the accuracy is not enough to distinguish between a raising or flat behavior. Independently of whether the measured ion distribution is compared to the universal parametrization (as shown in Fig. 4), the symmetric distribution of the Goldhaber formula or the measured positive-momentum side of the distribution, the same picture is obtained.

In the simple abrasion-ablation picture of the fragmentation, no products with more neutrons or protons than the projectile can be produced. However, experiments show that this happens even at very high, $E/A = 1$ GeV,

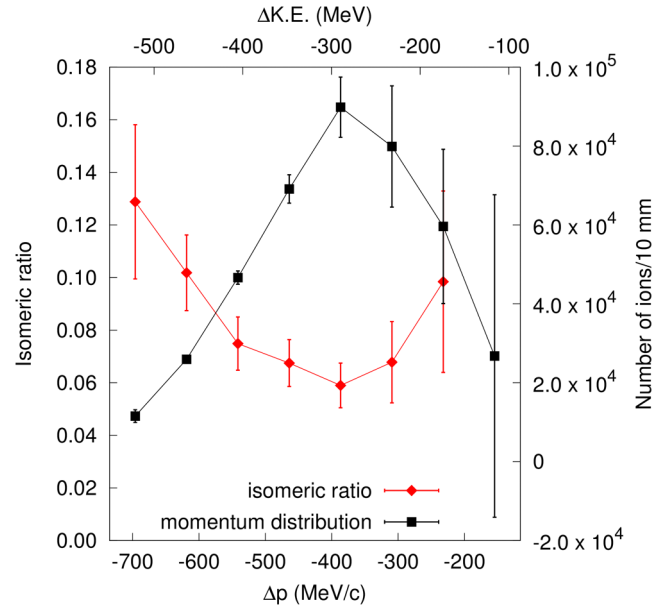


FIG. 4. Isomeric ratio of the “nonfragmentation” part of the reaction, after the pure fragmentation events are removed, as a function of momentum transfer. The momentum distribution of the nonfragmentation events is also shown. The upper scale shows the corresponding kinetic energy shift.

bombarding energy where the deep-inelastic reactions are negligible [6]. For example, $Z = 83$ Bi isotopes [30] and $N = 127$ isotones [31] were produced from ^{208}Pb projectiles. There are two different mechanisms at play here: (i) quasielastic collisions where a proton (neutron) takes over the total kinetic energy of a neutron (proton), and (ii) excitation of a proton (neutron) into a $\Delta(1232)$ -resonance state and its subsequent decay into a neutron (proton) via pion emission. The first mechanism does not modify the momentum of the fragment, while the second one reduces it due to the escaping pion, providing a way to disentangle the two processes experimentally [30,32]. Both of these processes can result in a reaction product with higher number of protons (or neutrons) than the initial ion. Therefore, we refer to these as nonfragmentation reactions. The charge pickup cross section is in reasonable agreement with the prediction of the intranuclear cascade model [33], which accounts for Δ production and its decay via pion emission. However, the population of individual excited states cannot be predicted in that model because the nuclear structure is treated in a rather rudimentary way—no shell structure is considered.

In addition to fragmentation, ^{54}Fe ($Z = 26$) can be produced also via the above processes, from ^{55}Co and ^{56}Co ($Z = 27$) prefragments. We note that the charge pickup reaction cross section is energy dependent [30] and it is at its highest at energies around $E/A = 500$ MeV, the energy used in the present experiment. All processes identified to populate the nucleus ^{54}Fe are illustrated in Fig. 5. The ones which involve excitation of the $\Delta(1232)$

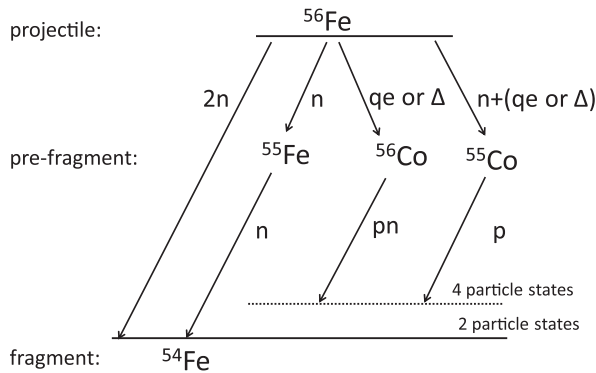


FIG. 5. Different reaction mechanisms populating ^{54}Fe from a relativistic energy collision of ^{56}Fe . Only those proceeding through the $^{55,56}\text{Co}$ prefragments can populate four particle states. The ones involving the $\Delta(1232)$ resonance result in a decreased momentum of the fragment. *qe* stands for quasielastic reaction.

resonance produce fragments with lower momentum, so they can readily account for the observed tail in the distribution. Also, while the main fragmentation process cannot populate four-particle states, the ones going through the $^{55,56}\text{Co}$ prefragments can.

The $^{55,56}\text{Co}$ prefragments can either decay via γ transitions to form $^{55,56}\text{Co}$ fragments or evaporate particles. In the latter case, proton evaporation, leading to iron isotopes, is favored as the proton separation energy is smaller by a factor of about 2 than the neutron separation energy in this neutron-deficient region of the nuclidic chart. The production cross section for both ^{55}Co and ^{56}Co is calculated within the intranuclear cascade model [13,33] to be around 3–4 mb, and we might assume a similar population probability of ^{54}Fe from both ^{55}Co and ^{56}Co . The ^{54}Fe production cross section from fragmentation is calculated to be 29.5 mb by the intranuclear cascade model [13,33], in good agreement with the 27.9 mb of the EPAX 3.1a parametrization [34]. The measured experimental ratio of momentum tail and symmetric momentum distribution of ^{54}Fe is $\approx 7\text{--}10\%$, in qualitative agreement with the above estimates. The average energy removed by the pion from the nucleus is around 300 MeV [6,30,35]. This value is in agreement with the measured energy loss of the fragment (see the secondary horizontal axis on Fig. 4).

It was previously observed that the population of high angular momentum states, $I > 15\hbar$, is higher than expected from fragmentation models [17,36,37]. However, the models do not consider nucleonic excitations. As shown in the present example, excitations of the Δ resonance (and possibly other higher-lying resonances) and its subsequent decay can produce additional angular momentum in the final fragment. This might account for the increased population of high-angular momenta states even in nuclei where there are enough valence nucleons from the start.

Conclusions.—The $I^\pi = 10^+$ isomeric state of ^{54}Fe was populated in the fragmentation of a ^{56}Fe beam at an energy of $E/A = 500$ MeV. This state has a four-nucleon configuration. Therefore, it cannot be populated by two neutron removal reactions. The isomer was populated in the low-energy tail of the ^{54}Fe distribution. The population of the isomer can be explained by considering inner excitations of a neutron, the Δ resonance. Other, higher-lying resonances might also play a role. The removed pion accounts for the lower kinetic energy, while in the process additional valence nucleons are created, contributing to the four-nucleon nature of the isomeric state.

The present result opens up the possibility to study the final nuclear states following the decay of in-medium $\Delta(1232)$ and other higher-lying resonances in relativistic energy heavy-ion collisions. The resonance production as well as the quantum state of the resulting nucleon after pion emission is expected to depend on the projectile as well as its energy. The existence of a large number of metastable states [38,39] allows the extension of the present work to other regions of the nuclidic chart. Experiments focusing on nuclei with the same atomic mass as the projectile are the most promising as these allow the direct investigation of the process, without the interference caused by additional neutron or proton emission.

We thank the GSI accelerator staff for their excellent work. Fruitful discussions with J. A. Tostevin, E. C. Simpson, and P. M. Walker are acknowledged. This work is supported by the STFC(UK), the Swedish Research Council, the German BMBF under Grants No. 05P15RD FN1, No. 05P12RDFN8, MINECO, Spain, under FPA2014-57196-C5, Generalitat Valenciana, Spain, under No. PROMETEOII/2014/019 and by the FEDER funds of the European Commission. This work has been supported by the European Community FP7–Capacities, ENSAR Contract No. 262010.

-
- [1] L. W. Alvarez and F. Bloch, *Phys. Rev.* **57**, 111 (1940).
 - [2] R. Frisch and O. Stern, *Z. Phys.* **85**, 4 (1933).
 - [3] M. Gell-Mann, *Phys. Lett.* **8**, 214 (1964).
 - [4] G. Zweig, *Developments in the Quark Theory of Hadrons* **1**, 22 (1980).
 - [5] J. Beringer *et al.* (Particle Data Group), *Phys. Rev. D* **86**, 010001 (2012).
 - [6] D. Bachelier *et al.*, *Phys. Lett. B* **172**, 23 (1986).
 - [7] Y. Ichigawa *et al.*, *Nat. Phys.* **8**, 918 (2012).
 - [8] C. B. Hinke *et al.*, *Nature (London)* **486**, 341 (2012).
 - [9] D. Steppenbeck *et al.*, *Nature (London)* **502**, 207 (2013).
 - [10] M. Thoenessen and B. M. Sherrill, *Nature (London)* **473**, 25 (2011).
 - [11] R. Bernas, E. Gradsztajn, H. Reeves, and E. Schatzman, *Ann. Phys. (N.Y.)* **44**, 426 (1967).
 - [12] J. J. Gaimard and K. H. Schmidt, *Nucl. Phys.* **A531**, 709 (1991).

- [13] A. Boudard, J. Cugnon, J.-C. David, S. Leray, and D. Mancusi, *Phys. Rev. C* **87**, 014606 (2013).
- [14] R. Grzywacz *et al.*, *Phys. Lett. B* **355**, 439 (1995).
- [15] M. Pfützner *et al.*, *Phys. Lett. B* **444**, 32 (1998).
- [16] Zs. Podolyák *et al.*, *Phys. Lett. B* **491**, 225 (2000).
- [17] Zs. Podolyák *et al.*, *Phys. Lett. B* **672**, 116 (2009).
- [18] H. Geissel *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. B* **70**, 286 (1992).
- [19] M. Pfützner *et al.*, *Phys. Rev. C* **65**, 064604 (2002).
- [20] S. Akkoyun *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **668**, 26 (2012).
- [21] N. Lalović *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **806**, 258 (2016).
- [22] O. Tarasov, *Nucl. Phys.* **A734**, 536 (2004).
- [23] A. S. Goldhaber, *Phys. Lett. B* **53**, 306 (1974).
- [24] D. Yan and J. Huo, *Nucl. Data Sheets* **121**, 1 (2014).
- [25] E. Dafni, J. W. Noé, M. H. Rafailovich, and G. D. Sprouse, *Phys. Lett. B* **78**, 1 (1978).
- [26] E. C. Simpson, J. A. Tostevin, D. Bazin, and A. Gade, *Phys. Rev. C* **79**, 064621 (2009).
- [27] E. C. Simpson, J. A. Tostevin, Zs. Podolyák, P. H. Regan, and S. J. Steer, *Phys. Rev. C* **82**, 037602 (2010).
- [28] E. C. Simpson, J. A. Tostevin, Zs. Podolyák, P. H. Regan, and S. J. Steer, *Phys. Rev. C* **80**, 064608 (2009).
- [29] D. Rudolph *et al.*, *Phys. Rev. C* **78**, 021301(R) (2008).
- [30] A. Kelić *et al.*, *Phys. Rev. C* **70**, 064608 (2004).
- [31] A. I. Morales *et al.*, *Phys. Rev. C* **84**, 011601(R) (2011).
- [32] C. Gaarde, *Annu. Rev. Nucl. Part. Sci.* **41**, 187 (1991).
- [33] D. Mancusi, A. Boudard, J. Cugnon, J.-C. David, P. Kaitaniemi, and S. Leray, *Phys. Rev. C* **90**, 054602 (2014).
- [34] K. Sümmerer, *Phys. Rev. C* **86**, 014601 (2012).
- [35] T. Udagawa, P. Oltmanns, F. Osterfeld, and S. W. Hong, *Phys. Rev. C* **49**, 3162 (1994).
- [36] M. Bowry *et al.*, *Phys. Rev. C* **88**, 024611 (2013).
- [37] A. M. Denis-Bacelar *et al.*, *Phys. Lett. B* **723**, 302 (2013).
- [38] P. M. Walker and G. D. Dracoulis, *Nature (London)* **399**, 35 (1999).
- [39] A. K. Jain, B. Maheshwari, S. Garg, M. Patial, and B. Singh, *Nucl. Data Sheets* **128**, 1 (2015).