Physics Letters B 753 (2016) 204–210

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Exclusive measurements of quasi-free proton scattering reactions in inverse and complete kinematics

V. Panin [a,*], J.T. Taylor [b], S. Paschalis [a], F. Wamers [a,c], Y. Aksyutina [c], H. Alvarez-Pol [d], T. Aumann [a], C.A. Bertulani [e], K. Boretzky [c], C. Caesar [a], M. Chartier [b], L.V. Chulkov [f], D. Cortina-Gil [d], J. Enders [a], O. Ershova [g], H. Geissel [c], R. Gernhäuser [h], M. Heil [c], H.T. Johansson [i], B. Jonson [i], A. Kelić-Heil [c], C. Langer [g], T. Le Bleis [h], R. Lemmon [j], T. Nilsson [i], M. Petri [a], R. Plag [c], R. Reifarth [g], D. Rossi [c], H. Scheit [a], H. Simon [c], H. Weick [c], C. Wimmer [g]

[a] Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany
[b] Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom
[c] GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
[d] Departamento de Física de Partículas, Universidade de Santiago de Compostela, 15706 Santiago de Compostela, Spain
[e] Department of Physics and Astronomy, Texas A&M University-Commerce, Commerce, TX 75429, USA
[f] Kurchatov Institute, Ru-123182 Moscow, Russia
[g] Goethe-Universität Frankfurt am Main, 60438 Frankfurt am Main, Germany
[h] Physik Department E12, Technische Universität München, 85748 Garching, Germany
[i] Fundamental Fysik, Chalmers Tekniska Högskola, S-412 96 Göteborg, Sweden
[j] STFC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom

ARTICLE INFO

Article history:
Received 17 August 2015
Received in revised form 12 November 2015
Accepted 30 November 2015
Available online 10 December 2015
Editor: V. Metag

Keywords:
Quasi-free scattering
Inverse kinematics
Single-particle states
Spectroscopic factors

ABSTRACT

Quasi-free scattering reactions of the type $(p, 2p)$ were measured for the first time exclusively in complete and inverse kinematics, using a ^{12}C beam at an energy of ∼400 MeV/u as a benchmark. This new technique has been developed to study the single-particle structure of exotic nuclei in experiments with radioactive-ion beams. The outgoing pair of protons and the fragments were measured simultaneously, enabling an unambiguous identification of the reaction channels and a redundant measurement of the kinematic observables. Both valence and deeply-bound nucleon orbits are probed, including those leading to unbound states of the daughter nucleus. Exclusive $(p, 2p)$ cross sections of 15.8(18) mb, 1.9(2) mb and 1.5(2) mb to the low-lying $0p$-hole states overlapping with the ground state $(3/2^-)$ and with the bound excited states of ^{11}B at 2.125 MeV $(1/2^-)$ and 5.02 MeV $(3/2^-)$, respectively, were determined via γ-ray spectroscopy. Particle-unstable deep-hole states, corresponding to proton removal from the $0s$-orbital, were studied via the invariant-mass technique. Cross sections and momentum distributions were extracted and compared to theoretical calculations employing the eikonal formalism. The obtained results are in a good agreement with this theory and with direct-kinematics experiments. The dependence of the proton–proton scattering kinematics on the internal momentum of the struck proton and on its separation energy was investigated for the first time in inverse kinematics employing a large-acceptance measurement.

© 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

Nuclear spectroscopy is one of the most fascinating areas of science, with applications in cosmology, stellar evolution, and even seemingly unrelated research areas such as material science. A strong confidence on the role of single-particle (SP) states in nuclear structure and nuclear spectroscopy arose with the work of Wigner, Mayer, and Jensen, recipients of the 1963 Nobel Prize, through the discovery and application of fundamental symmetry principles to nuclei and for realizing that much of the trend of nuclear masses and their energy spectra could be well understood by means of a simple SP shell model [1–3].

* Corresponding author at: RIKEN Nishina Center, RIBF Building 3F, 2-1 Hirosawa, Wako 351-0198, Japan. Tel.: +81 48 462 7946.
E-mail address: valerii.panin@riken.jp (V. Panin).

http://dx.doi.org/10.1016/j.physletb.2015.11.082
0370-2693/© 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

With the technical possibility of exploring nuclei far from the valley of β stability it was soon realized that the SP structure of nuclei is more of a local concept and it evolves with increasing proton–neutron asymmetry, at odds with the theoretical predictions. This shell evolution arises from terms in the nuclear interaction, which are not treated explicitly in the shell model, and which are enhanced only in neutron–proton asymmetric nuclei, placing their spectroscopy at the frontier of modern nuclear physics.

The large potential of studying the SP properties of nuclei by means of quasi-free nucleon–nucleon scattering (QFS) at high energy has been already realized by Chamberlain and Segrè [4] when they first observed this process pointing out the sensitivity to the intrinsic nucleon momentum distribution. Since then, QFS reactions of the type $(p, 2p)$ have been extensively used to study stable nuclei, see Refs. [5,6] for a review, and the work of Yosoi et al. [7] for a recent high-resolution measurement.

For the investigation of the shell structure of short-lived nuclei, nucleon-removal reactions have been employed in inverse kinematics using composite targets such as beryllium or carbon [8–10]. However, the sensitivity of such heavy-ion induced nucleon removal reactions is limited to the nuclear surface [11] and thus limits the accessible range of the bound-nucleon wave function, especially when a nucleon is removed from a deeply-bound shell in the case of exotic nuclei. In contrast to this, QFS reactions of $(p, 2p)$ and (p, pn) type are known to be sufficiently sensitive to both valence and deeply-bound shells [5,6,12].

In this Letter we present a new experimental approach to QFS reactions via inverse and complete kinematics measurements with a large-acceptance detection system. This technique results in minimum limitations on the observed kinematics (*e.g.*, scattering angles, energies, coplanarity, *etc.*) and provides complete information on the scattering process as well as on the structure of individual SP states. So far, proton-induced knockout reactions have been employed in inverse kinematics only in a more inclusive manner [13,14]. Furthermore, QFS in inverse kinematics is a very promising tool to investigate the role of nucleon–nucleon short-range correlations in neutron–proton asymmetric nuclei, including those induced by the tensor force, see Refs. [15,16] for two recent results from electron-induced knockout on stable nuclei. For such cases, the measurement in inverse kinematics offers the possibility to observe both the three outgoing nucleons as well as the beam-like heavy residue in coincidence.

Ideally, proton-induced QFS reaction is a sudden process with respect to internal motions of the nucleons in the nucleus in which a proton scatters elastically off a bound nucleon and both particles escape the nucleus without further interactions [5]. This creates a hole in the corresponding SP state, which can overlap with the ground state of the daughter nucleus or decay via γ-ray or particle emission, depending on the residual excitation energy E_x in the $(A-1)$ system and therefore on the separation energy $S_n = Q_n + E_x$ of the ejected nucleon, where Q_n is the nucleon separation threshold. Spectroscopic properties of the involved SP state, such as separation energy and internal momentum, can be extracted in two ways:

(i) by measuring the momenta of the recoil nucleons,
(ii) via direct measurement of the de-excitation of the $(A-1)$ system and its recoil momentum.

In direct-kinematics experiments, however, in which energetic protons irradiate stationary nuclear targets, the latter approach (ii) is very challenging. This is due to a relatively small momentum of the nuclear recoil, which prevents its escape from the target and complicates measurements of particle-unstable residual states. For this reason, detailed structure and fragmentation of deep-hole states are poorly known even in light stable nuclei [7]. In contrast, inverse kinematics in conjunction with full solid-angle coverage enables a redundant kinematical measurement of QFS reactions; this in turn allows a detailed study of correlations and final-state interactions to identify two-step processes.

The simplicity of the QFS reaction mechanism enables the use of the impulse approximation, which factorizes the reaction amplitude into a term associated with the elementary two-nucleon elastic scattering and a term corresponding to the nuclear part of the interaction alone [17]. However, there are two main sources of corrections entering the theoretical interpretation of experimental data. The first one is nuclear absorption, which can be taken into account by a complex optical potential which distorts the single-nucleon wave function [5,6,12]. The second one is purely technical and depends on the specific geometry of the experiment, *i.e.*, on angular and energy ranges of the measured nucleon pairs, which inevitably impose constraints on the observable energy and momentum space of the SP state as it is demonstrated in this Letter. In particular, most of the direct-kinematics QFS experiments so far have been performed in coplanar geometry, and only very few attempts were made to study experimentally and theoretically non-coplanar reactions [18–23]. Hence, large-acceptance experiments can become useful in extracting this information, although the absorption effects must still be taken into account carefully [22].

We are reporting on an experiment which was performed at the GSI Helmholzzentrum für Schwerionenforschung in Darmstadt, using the R^3B prototype setup [24], schematically shown in Fig. 1. A primary ^{12}C beam at an energy of 400 MeV/u was extracted from the heavy-ion synchrotron SIS18 and directed onto a 213(4) mg/cm^2 thick CH_2 target. The beam energy in the middle of the CH_2 target was $\sim$397.8 MeV/u. Complementary measurements with a 370(7) mg/cm^2 pure carbon target were carried out in order to extract the reaction contribution of the hydrogen component in the CH_2. Outgoing pairs of QFS protons were measured in the 4π-calorimeter Crystal Ball (CB), consisting of 159 NaI(Tl) crystals. Gamma-rays stemming from de-excitation of residual nuclei were also detected in the CB calorimeter. Additionally, the reaction chamber was equipped with an array of six AMS-type [25] 300 μm thick double-sided silicon-strip detectors (DSSDs) with a pitch of $\sim$100 μm. Four DSSDs downstream of the target aimed at the detection of QFS protons and covered the solid angle ranging from approximately 14° to 64° in the polar direction relative to the beam axis and to the geometrical center of the target. The two other DSSDs were placed on the beam axis at distances of 11 cm and 13.5 cm downstream of the target for charge identification and position measurements of kinematically forward-focused reaction fragments. The large dipole magnet ALADIN was situated at a distance of 1.5 m after the target and was used for separating heavy reaction products from breakup protons and neutrons. Each type of particle was separately measured after the magnet using time-of-flight Δt, energy-loss ΔE, and position information (x, y, z) in the corresponding tracking systems as shown in Fig. 1. Mass and charge resolutions below 3% were reached for the tracked $Z = 5$ fragments. Kinematically forward-focused neutrons from in-flight decay of excited fragments were detected around zero degree polar angle, using the Large Area Neutron Detector (LAND) [26] at a distance of around 14 m downstream of the target. Combining data from the different tracking arms allowed for the invariant-mass reconstruction of unbound $(A-1)$ fragments. Coarse angular information from two high-energy hits in the forward hemisphere of the CB was used to identify coincident proton hits in the DSSDs. Their outgoing angles were then reconstructed relative to the vertex in the target, which was obtained via backward tracking of the heavy fragment measured in the two in-beam DSSDs. Since the

Download English Version:

https://daneshyari.com/en/article/1850487

Download Persian Version:

https://daneshyari.com/article/1850487

Daneshyari.com