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ScienceDirect

Nuclear Data Sheets 120 (2014) 84–87

Nuclear Data Sheets

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Precise Lifetime Measurements in Light Nuclei for Benchmarking Modern Ab-initio Nuclear Structure Models

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A new generation of ab-initio calculations, based on realistic two- and three-body forces, is having a profound impact on our view of how nuclei work. To improve the numerical methods, and the parameterization of 3-body forces, new precise data are needed. Electromagnetic transitions are very sensitive to the dynamics which drive mixing between configurations. We have made a series of precise (<3%) measurements of electromagnetic transitions in the A=10 nuclei ^{10}C and ^{10}Be by using the Doppler Shift Attenuation method carefully. Many interesting features can be reproduced including the strong α clustering. New measurements on ^{8}Be and ^{12}Be highlight the interplay between the alpha clusters and their valence neutrons.

I. INTRODUCTION

Ideally, one would like to describe all nuclear systems from the most fundamental level of quarks and gluons. However, the span of energy and length scales and the complexity of the force appears to make a single theory intractable in the foreseeable future. The central theme of contemporary nuclear structure physics is to produce a set of closely-linked models which can build up starting from quarks and gluons, to nucleons and the inter-nucleon forces, then using these forces to describe light nuclei and the rise of the mean field and effective forces, and hence to configuration-mixing models for middle-mass nuclei, and finally to density functional theories to describe the heaviest nuclei with many hundreds of nucleons. The key issue in this hierarchy is to retain the important physics at each level of truncation and avoid arbitrary renormalizations. As we move from the well-known nuclei along the valley of stability, to the drip lines and up to the very heaviest nuclei, we need to better understand the evolution of nuclear matter as it becomes more and more exotic. This is especially true for nuclei with large neutron excesses, where our predictive power of nuclear structure is poorest, but where most heavy nucleosynthesis occurs. The lessons we can learn from the nuclei that we can synthesize on earth provide the only guide we have to some of the most exotic nuclear material that we think exists in the universe, for example in the crusts of neutron stars. Paradoxically then, studying the lightest nuclei very carefully can teach us a great deal about the heaviest nuclear systems in the cosmos.

A wide variety of new nuclear models are forging the links between bare nuclear forces and nuclear structure. In this paper we will concentrate on testing the Green's Function Monte Carlo (GFMC) approach of Pieper and Wiringa [1, 2], as it is these calculations which motivated our experimental campaigns. However, other approaches, including "No Core" shell models [3, 4], effective field theories [5], lattice-based approaches [6, 7] and cluster models [8, 9] are similarly motivated. To really challenge these models, a new generation of precise experiments has started, especially in light nuclei. Mass measurements [10, 11] and RMS radii [12–14] test the overall binding and topology of the wave functions, while sub-barrier fusion [15, 16], knockout [17] and transfer reactions [18] are all sensitive to the radial parts of the wave function. In this paper, we will discuss the measurement of precise electromagnetic transitions [19, 20] as a useful additional tool for investigating how different nuclear configurations mix. In all these tests, there is an interesting interplay of improving the actual computational methods and convergence, and developing improved nuclear forces. The computations involve massively parallel computing and most of them were simply not feasible until this century.

The approach of Pieper and Wiringa starts from the Argonne V18 two-body force [21], which is quite well known and is constrained by thousands of measurements, so is kept fixed. Constructing a proper nuclear wave function and minimizing its energy with just a two-body never produces enough binding energy. A key early finding was that three-body and higher correlations are essential to reproduce the known binding energy of light systems [22]. This presents a challenge, as these higher correlations are far less well understood and constrained by measurements. Thus, some unknown parameters must be intro-

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http://dx.doi.org/10.1016/j.nds.2014.07.013

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duced and fitted. However, over the last two decades the Illinois school has developed a series of three body interactions which capture more and more of the essential physics [23]. These correlations contribute $\sim$10% of the binding energy, but are responsible for half of the effective spin-orbit and tensor forces. They have strong isospin dependence, so are crucial for understanding exotic nuclei with large neutron excesses. They are most influential when the nucleons are close together, so are very significant in "clusters" of nucleons. Consequently, a good place to further investigate three-body forces is in the most clustered nuclei, like helium, beryllium, and carbon isotopes. This was the reason for choosing the beryllium isotopes ^{8,10,12}Be for our particular attention. Beryllium at heart is a di-alpha cluster, which can tumble end-over-end, and emit electromagnetic radiation. The rate of radiation is directly related to the size of the radiating antenna, that is, the alpha-cluster spacing, so a precise measurement of the decay rate gives the state lifetime, and directly reveals the cluster spacing, the influence of "valence" neutrons, and the mixing of "tumbling" with other configurations. The experimental challenge is refining precision from the level of tens of percent achieved in the 1960's to the few percent level in the transitional matrix elements.

II. EXPERIMENTS ON BERYLLIUM ISOTOPES

The state of interest, the "tumbling" state, is known to have a lifetime of $\sim$200 fs so is amenable to the Doppler Shift Attenuation Method (DSAM) [24]. To employ this method, the excited state of interest should be formed in a nuclear reaction in which the parent nucleus is produced with a high and well determined velocity. When the state decays by gamma emission, the radiation observed in the laboratory is then Doppler Shifted. The measured energy of the gamma ray depends on the intrinsic energy difference between the states under study, on the detection angle of the gamma rays and on the parent velocity. If the state decayed instantly, the velocity inferred from the Doppler shift would match the production velocity (which can be calculated from reaction kinematics). However, if the nucleus is de-accelerating, then the Doppler Shift is reduced. Only slowing the nuclei in solid materials can achieve the degree of de-acceleration needed for studying these short-lived states. The reduction of shift depends on a convolution of the slowing history and on the lifetime of the state. If the slowing history is known, then the lifetime can be inferred. Our experimental method is simply to do this measurement with careful attention to detail.

- We use 2-body reactions, in inverse kinematics and with large Q-values to make the nuclei recoil fast, thus increasing the size of Doppler shifts. In our ^{10}C project [20] the initial recoil velocity was $\sim$12%c.
- We use very thin production targets to make the initial ensemble have uniform velocity.
- We detect the recoiling nucleus in a spectrometer, the Argonne Fragment Mass Analyzer (FMA) [25] in a small recoil cone near zero degrees. This helps determine the recoil-gamma opening angle, removes backgrounds from other reactions, and allows us to select reactions that directly populates our state of interest.
- We detect the gamma rays at 16 different angles, using the national gamma ray facility Gammasphere [26]. This allows many cross-checks and tests for systematic uncertainties. For example, we can detect a mis-alignment of the target of <1 mm.
- We use different slowing materials, like aluminum, copper, tantalum, and gold, and targets of different thicknesses, to cross check our modeling of slowing and the stopping powers [27, 28]. In the 1960's, the paucity of data on stopping of ions in materials was the leading limitation of this technique, but vast progress has been made both in modeling and measurement, so in the velocity regime we use, the stopping powers are known at the few percent level.

In short, these studies revealed several things. Technically, very precise DSAM is possible. Figure 1 illustrates this precision using data from our ^{10}C measurement. The average velocity of the nucleus when the γ-ray is emitted can be measured to very high precision (<1%), as given in Fig. 1 (top). In turn, the data are very sensitive to the lifetime of the level, as shown in Fig. 1 (bottom). We believe the current limitation is targetry: knowing exactly the composition and thickness of the production layers is a key. We worry about non-uniformity of thickness on the less than mm scale, i.e. across the beam spot. Another concern is deterioration of the targets under bombardment: do they retain their thickness? These things can be monitored by moving the beam, changing the target often, monitoring yield with time, but they are the leading uncertainties. Perhaps nano-technology will come to the rescue and allow fabrication of targets by atomic layer deposition. In physics, the GFMC proved reliable in predicting the overall topology of the antenna; that is the total quadrupole strength. We measured the sum of the $B(E2)$ values from the first and second J^π=2$^+$ states in ^{10}Be as 9.3(3) e^2fm^4 and the calculation predicted 10.5(3) e^2fm^4 [19]. The projection of the density distribution of these wave functions clearly show both the two distinctly separated alpha clusters and the near-spherical cloud of neutrons. What was not quite so good is the configuration mixing. In nature, the first J^π=2$^+$ state comes from "tumbling" of the di-alpha cluster, that is, it is the first member of the ground-state band, while the second J^π=2$^+$ state arises from re-coupling the two valence neutrons from J=0 to J=2. In nature, it turns out that these modes are very decoupled, with the neutron re-coupled state radiating 80 times slower. Nature clearly likes this symmetry. In GFMC, with all its sophistication, there

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