Exotic nucleus in the medium mass region: the curious case of ^{34}Na

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Introduction

Coulomb dissociation (CD) has emerged to be an important tool to study the exotic structure of nuclei, especially in the drip line region. In principle, it is the photo-absorption by a projectile while moving in the varying Coulomb field of a stable, heavy target and then disintegration of the same into a core and a (or more) nucleon(s) [1].

Advances in experimental sophistication have generated interest in exotic nuclei in the medium mass region which are also speculated to form connecting links within the various reaction chains that produce energy to power the stars (s-process, r-process, rp-process, etc.). Thus, it is essential to know their structure and properties as these can then be used to calculate their reaction-rates. These reaction-rates help us to predict the element production or nucleosynthesis in stellar plasma [2].

^{34}Na is one such exotic nucleus lying close to the neutron drip line. Recent experiments have shown that the one neutron separation energy (S_n) for ^{34}Na is (0.17 ± 0.50) MeV [3], while the NNDC database [4] displays the same to be ≃ (0.75 ± 0.008) MeV. Thus, the uncertainty is too large to be ignored. Moreover, the ground state spin-parity and shape (spherical or deformed) are some of the other aspects that need to be established for ^{34}Na as strongly deformed nuclei have been found in the medium mass region with $N \approx 20$. Going by the trends in this region, it is probable that the ground state of ^{34}Na has a dominant p-wave contribution [3, 5]. In this text, we intend to use the CD method to calculate the different reaction observables like total cross-sections, relative energy spectra, momentum and angular distributions, etc., and investigate the possible allowed ground state configurations for ^{34}Na and its binding energy.

Formalism

Consider a beam of ^{34}Na at 100 MeV/u on a ^{208}Pb target which under the influence of the strong Coulomb repulsion from the ^{208}Pb nucleus, breaks up into ^{33}Na and a neutron, i.e.,

$$^{34}\mathrm{Na} + {}^{208}\mathrm{Pb} \longrightarrow {}^{33}\mathrm{Na} + \mathrm{n} + {}^{208}\mathrm{Pb}.$$

We consider elastic breakup and use the finite range distorted wave Born approximation (FRDWBA) theory. We calculate the triple differential cross section and then integrate it to find the one neutron removal cross-section (σ_{-1n}) of the above mentioned breakup reaction.

The triple differential cross-section is given by,

$$\frac{d\sigma}{dE_{rel}\Omega_{at}\Omega_{bc}} = \frac{2\pi}{\hbar v_{at}}\rho_{(phase)}\sum_{l,m}|\beta_{lm}|^2 \quad (1)$$

with a being the ^{34}Na projectile, t is the ^{208}Pb target, b the ^{33}Na core and c is the valence nucleon (which in the present case happens to be a neutron). E_{rel} is the b-c relative energy in the final channel, v_{at} is the a-t relative velocity in the initial channel, Ω's are the solid angles of the a-t and b-c systems, respectively and $\rho_{(phase)}$ is the phase factor. Also, the reduced amplitude β_{lm} as defined in the FRDWBA is:

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$$\beta_{lm}^{FRDWBA} = \iint d\mathbf{r}_1 d\mathbf{r}_i \chi_b^{(-)*}(\mathbf{q}_b, \mathbf{r}) \\ \chi_c^{(-)*}(\mathbf{q}_c, \mathbf{r}_c) V_{bc}(\mathbf{r}_1) \\ \phi_a^{lm}(\mathbf{r}_1) \chi_a^{(+)}(\mathbf{q}_a, \mathbf{r}_i) \tag{2}$$

In Eq. (2), the $\mathbf{r}$'s are the position vectors of the particles according to the Jacobi coordinate system, χ's represent the pure Coulomb distorted waves with incoming [(-)] and outgoing [(+)] wave boundary conditions and $\phi_a^{lm}(\mathbf{r}_1)$ is the ground state wavefunction of a having angular momentum l and projection m. The deformation enters our theory via the deformed potential V_{bc} in Eq. (2). We are able to semi-analytically factorize the breakup amplitude in two parts: one, the dynamics part (which can be evaluated analytically) and two, the structure part (which essentially contains the effects of deformation).

For further details on the formalism, one may refer to [5, 6].

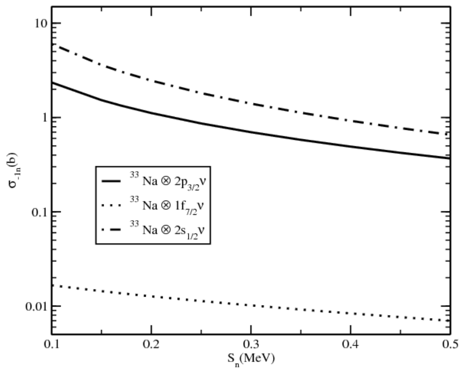

FIG. 1: The total cross-section vs one neutron separation energy for ^{34}Na breaking on ^{208}Pb at 100 MeV/u beam energy to form a ^{33}Na core and a neutron. The deformation parameter, β_2 has been set to 0.

Results and discussion

In Fig. 1 we present the total one neutron removal cross-section (σ_{-1n}) for the breakup of ^{34}Na on a ^{208}Pb target at 100 MeV/u beam energy as a function of one neutron separation energy (S_n) for different possible cases of ground state configurations ($J^\pi = 1/2^+, 3/2^-, 7/2^-$) of ^{34}Na. The ^{33}Na core has a ground state spin-parity of $3/2^+$ and the deformation parameter is taken to be zero for the present calculation.

It can be clearly seen that the cross-section for the $1f_{7/2}$ state is orders of magnitude lesser than the cross-sections for $2s_{1/2}$ or $2p_{3/2}$ states. We will also present calculations for the total cross-section as a function of quadrupole deformation, β_2, and separation energy as parameters as well as the results for the momentum and angular distributions and relative energy spectra.

To conclude, we will use our semi-analytical yet fully quantum mechanical theory to predict the consequences of deformation effects on the ground state spin-parity of ^{34}Na which is expected to be dominated by the $2p_{3/2}$ state. This will be interesting for experimental as well as theoretical purposes in the region of medium mass exotic nuclei.

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