Quasireal photons in nucleus-nucleus collisions at intermediate and high energies, applications to nuclear structure, nuclear astrophysics and particle physics

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1 Introduction

It is interesting to study nuclear collisions where the colliding nuclei interact only electromagnetically. This can be achieved by using bombarding energies below the Coulomb barrier or by choosing very forward scattering angles in high energy collisions. With increasing beam energy states at higher excitation energies can be excited; this can lead, in addition to Coulomb excitation, also to Coulomb dissociation [1]. Such experiments are also feasible with secondary (radioactive) beams. Because Coulomb dissociation is generally well understood theoretically, there can be a clean interpretation of the experimental data. This is of interest for nuclear structure and nuclear astrophysics [2, 3, 4]. It is the purpose of this lecture to give an overview of the theoretical methods and to discuss the experimental results.

Multiple electromagnetic excitation can also be important. We mention two aspects: it is a means to excite new nuclear states, like the double phonon giant dipole resonance [4]; but it can also be a correction to the one-photon excitation [5, 6, 7].

The cross sections of such processes rise logarithmically with energy. This leads to strong effects in the scattering of relativistic beams, especially heavy ions. Even though this would merit a lecture of its own, the production of antihydrogen (\(\bar{\text{H}}\)) at LEAR and FERMILAB and electromagnetic processes at the relativistic heavy ion colliders RHIC and LHC are briefly mentioned.

2 Theory of electromagnetic excitation and dissociation

2.1 Inelastic scattering at high energies: one-photon exchange, semiclassical approach and Glauber theory

In the equivalent photon approximation the cross section for an electromagnetic process is written as

\[
\sigma = \int \frac{d\omega}{\omega} n(\omega)\sigma_\gamma(\omega)
\]  

(1)

where \(\sigma_\gamma(\omega)\) denotes the corresponding cross section for the photo-induced process and \(n(\omega)\) is called the equivalent photon number. For high enough beam energies it can be well approximated by

\[
n(\omega) = \frac{2}{\pi} Z^2 \alpha \ln \frac{\gamma v}{\omega R}
\]  

(2)
where $R$ denotes some cut-off radius. More refined expressions, which take the dependence on multipolarity, beam velocity or Coulomb-deflection into account, are available in the literature [1, 6, 8].

The theory of electromagnetic excitation is well developed, for nonrelativistic as well as relativistic projectile velocities. In the latter case, an analytical result for all multipolarities was obtained in ref. [8]. The projectile motion was treated classically in a straight-line approximation. Using Glauber theory, the projectile motion can be treated quantally [1, 7, 9, 10, 11]. This gives rise to characteristic diffraction effects. The main effect is due to the strong absorption at impact parameters less than the sum of the two nuclear radii. Effects due to nuclear excitation have also to be taken into account [10, 12]. They are generally small and show a characteristic angular dependence, which can be used to separate such effects from electromagnetic excitation.

2.2 Higher order electromagnetic effects, small $\xi$-approximation

Higher order effects can be considered in a coupled channels approach, or using higher order perturbation theory. This involves a sum over all intermediate states considered to be important. Another approach is to integrate the time-dependent Schrödinger equation directly for a given model Hamiltonian [13].

If the collision is sudden one can neglect the time ordering in the usual perturbation approach. The interaction can be summed up to infinite order. In order to obtain the excitation cross section, one has to calculate the matrix-element of this operator between the initial and final state (i.e. the intermediate states do not appear explicitly). A related approach was developed for small values of $\xi$ in Refs. [5, 6, 7]. In a simple zero range model for the neutron-core interaction, analytical results were obtained for 1st and 2nd order electromagnetic excitation [5].

In such a model — a prototype for a loosely bound system, like the deuteron — there is only one bound state (s-wave). The continuum states are plane waves, except that the $l = 0$ partial wave is modified by the short range potential. Electromagnetic excitation is treated in the semiclassical straight line approximation. This system is described by a few scaling variables, the binding energy

$$E_0 = \frac{\hbar^2 \eta^2}{2m},$$

the strength parameter

$$\chi = \frac{2Z_X Z_{eff}^{(1)} e^2}{v \hbar k}(a = c + n),$$

where

$$Z_{eff}^{(1)} = -\frac{Z_c m_n}{m_c + m_n},$$

and

$$k = \sqrt{\eta^2 + q^2}$$

with $q$ = wave number in the continuum. $Z_X$ is the charge number of the target. The dipole excitation amplitude is given by

$$a_{f0}(q) = a_{f0}^{(1)}(q) + a_{f0}^{(2)}(q) = \sum_{\lambda\mu} C_{\lambda\mu}(q, \eta, \chi, \xi) Y_{\lambda\mu}(\hat{q}).$$

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The coefficients $C_{\lambda\mu}$ are given analytically (eqs. 27 – 32, Ref. [5]). Higher order effects depend essentially on the strength parameter $\chi$. From eq. 4 it is seen that higher order effects become more important with $Z_X$, decreasing impact parameter $b$ and velocity $v$ of the projectile, as is intuitively obvious.

3 Discussion of experimental results for nuclear structure

In recent years, electromagnetic excitation of intermediate energy (exotic) beams has been developed into a useful spectroscopic tool [14, 15]. By measuring the excitation energies of the first $2^+$ states and the corresponding $B(E2)$-values, nuclear structure effects, like deformation, can be studied in a unique way for nuclei far off stability. Electromagnetic excitation of the 1st excited state in $^{11}$Be has been studied experimentally at GANIL [16], RIKEN [17] and MSU [18]. This is a good test case, since the $B(E1)$-value of the corresponding ground-state transition is known already. Theoretical considerations [19, 20] show that higher order effects are expected to be small.

Coulomb dissociation of exotic nuclei is a valuable tool to determine electromagnetic matrix-elements between the ground state and the nuclear continuum. The excitation energy spectrum of the $^{10}$Be+n system in the Coulomb dissociation of the one-neutron halo nucleus $^{11}$Be on a Pb target at 72-A MeV was measured [21]. Low lying E1-strength was found. In a similar way, the Coulomb dissociation of the 2n-halo nucleus $^{11}$Li was studied in various laboratories. In an experiment at MSU [22] the correlations of the outgoing neutrons were studied. Within the limits of experimental accuracy, no correlations were found.

4 Coulomb dissociation as a tool to measure radiative capture processes relevant to nuclear astrophysics

In nuclear astrophysics, radiative capture reactions of the type

$$b + c \rightarrow a + \gamma \quad (8)$$

play a very important role. They can also be studied in the time-reversed reaction

$$\gamma + a \rightarrow b + c \quad (9)$$

at least in those cases where the nucleus $a$ is in the ground state. As a photon beam, we use the equivalent photon spectrum which is provided in the fast peripheral collision. Recent reviews, both from an experimental as well as theoretical point of view have been given [2], so we want to concentrate here on a few points.

The $^6$Li $\rightarrow \alpha + d$ Coulomb dissociation has been a test case of the method, as reviewed in Ref. [2]. The issue of primordial $^6$Li as a test of big bang nucleosynthesis has recently been discussed in Ref. [23]. The abundances of the lighter isotopes, notably $^4$He but also $^2$H, $^3$He, and $^7$Li have all been found to be consistent with the primordial level predicted
by the big bang nucleosynthesis over a fairly narrow range of the baryon to photon ratio $\eta$: $2.5 \cdot 10^{-10} < \eta < 6 \cdot 10^{-10}$. $^6$Li has the next highest predicted primordial abundance. The observation of primordial $^6$Li is not within reach of present experimental capabilities, but must be subjected to future techniques [23]. The key nuclear input is the cross section for the capture reaction $\alpha(d,\gamma)^6$Li at $E \approx 60 - 400$ keV. The astrophysical S-factor has been studied theoretically in Ref. [24] and [25]. In Ref. [24] a significant energy dependence of $S_{24}$ at astrophysical energies was found. At energies less than 110 keV, the E1 component was found to dominate over the E2 component. The agreement with the experimental results from Coulomb dissociation [26] is quite good.

The $^7$Be(p,$\gamma)^8$B radiative capture reaction is relevant to the solar neutrino problem. It determines the production of $^8$B which leads to the emission of high energy neutrinos. There are direct capture measurements, for a recent one see [27]. A significantly smaller value than previously adopted has been found there. Coulomb dissociation of $^8$B $\rightarrow$ $^7$Be $+ p$ has been studied at intermediate energies at RIKEN [28], MSU [29] and GSI [30], and, at rather low energies, at Notre Dame [31]. Up to now, only the RIKEN experiment has extracted an astrophysical S-factor from the data. We note that a model-independent separation of E1 and E2 components is possible by a careful study of angular distributions and correlations [29, 32, 33]. Furthermore, at RIKEN or higher energies, nuclear or higher order electromagnetic effects are virtually negligible. It can be hoped that a consistent picture will emerge for all these studies under different experimental conditions leading to the same astrophysical S-factor.

Other interesting cases could be the $^7$Li $\rightarrow$ $\alpha + t$ and $^7$Be $\rightarrow$ $\alpha + ^3$He Coulomb dissociation reactions. New theoretical results on the radiative capture reactions are given in [24].

Nucleosynthesis beyond the iron peak proceeds mainly by the r- and s-processes (rapid and slow neutron capture) [35, 36]. To establish the quantitative details of these processes, accurate energy-averaged neutron-capture cross sections are needed. Such data provide information on the mechanism of the neutron-capture process and time scales, as well as temperatures involved in the process. The data should also shed light on neutron sources, required neutron fluxes and possible sites of the processes (see Ref. [35]).

With the new radioactive beam facilities (either fragment separator or ISOL-type facilities) some of the nuclei far off the valley of stability, which are relevant for the r-process, can be produced. In order to assess the r-process path, it is important to know the nuclear properties like $\beta$-decay half-lives and neutron binding energies. Sometimes, the waiting point approximation [35, 36] is introduced, which assumes an (n,$\gamma$)- and ($\gamma$,n)-equilibrium in an isotopic chain. It is generally believed that the waiting point approximation should be replaced by dynamic r-process flow calculations, taking into account (n,$\gamma$), ($\gamma$,n) and $\beta$-decay rates as well as time-varying temperature and neutron density. In slow freeze-out scenarios, the knowledge of (n,$\gamma$) cross sections is important.

In such a situation, the Coulomb dissociation can be a very useful tool to obtain information on (n,$\gamma$)-reaction cross sections on unstable nuclei, where direct measurements cannot be done. Of course, one cannot and need not study the capture cross section on all the nuclei involved; there will be some key reactions of nuclei close to magic numbers. Quite recently, it was proposed [37] to use the Coulomb dissociation method to obtain information about (n,$\gamma$) reaction cross sections, using nuclei like $^{124}$Mo, $^{126}$Ru, $^{128}$Pd and $^{130}$Cd as projectiles. The optimum choice of beam energy will depend on the actual neutron binding energy. Since the flux of equivalent photons has essentially an $\omega^{-1}$ dependence,
low neutron thresholds are favourable for the Coulomb dissociation method. Note that only information about the \((n,\gamma)\) capture reaction to the ground state is possible with the Coulomb dissociation method. The situation is reminiscent of the loosely bound neutron-rich light nuclei, like \(^{11}\)Be and \(^{11}\)Li. In these cases, the Coulomb dissociation has proved very useful (see the discussion above).

In Ref. [5] the 1\(^{st}\) and 2\(^{nd}\) order Coulomb excitation amplitudes are given analytically in a zero range model for the neutron-core interaction (see section 2.2). This can be very useful to assess how far one can go down in beam energy and still obtain meaningful results with the Coulomb dissociation method. I.e., where the 1\(^{st}\) order amplitude can still be extracted experimentally without being too much disturbed by corrections due to higher orders. For future radioactive beam facilities, like ISOL od SPIRAL, the maximum beam energy is an important issue. We propose to use the handy formalism of Ref. [5] to assess, how far one can go down in beam energy. For Coulomb dissociation with two charged particles in the final state, like in the \(^{8}\)B \(\rightarrow\) \(^{7}\)B + p experiment with a 26 MeV \(^{8}\)B beam [31] such simple formulae seem to be unavailable and one should resort to the more involved approaches mentioned in section 2.2.

A new field of application of the Coulomb dissociation method can be two nucleon capture reactions. Evidently, they cannot be studied in a direct way in the laboratory. Sometimes this is not necessary, where the relevant information about resonances involved can be obtained by other means (transfer reactions, etc.), like in the triple \(\alpha\)-process.

Two-neutron capture reactions in supernovae neutrino bubbles are studied in [39]. In the case of a high neutron abundance, a sequence of two-neutron capture reactions, \(^{4}\)He(2n,\(\gamma\))\(^{6}\)He(2n,\(\gamma\))\(^{8}\)He can bridge the \(A = 5\) and 8 gaps. The \(^{6}\)He and \(^{8}\)He nuclei may be formed preferentially by two-step resonant processes through their broad 2\(^{+}\) first excited states [39]. Dedicated Coulomb dissociation experiments can be useful. Another key reaction can be the \(^{4}\)He(\(\alpha\)n,\(\gamma\)) reaction [39]. The \(^{9}\)Be(\(\gamma\),n) reaction has been studied directly (see Ref. [40]) and the low energy \(s_{\frac{1}{2}}\) resonance is clearly established. Despite this, a \(^{9}\)Be Coulomb dissociation experiment could be rewarding (cf. also Ref. [41]). Other useful information is obtained from \((e,e')\) and \((p,p')\) reactions on \(^{9}\)Be [42].

In the rp-process, two-proton capture reactions can bridge the waiting points [38, 43, 44]. From the \(^{15}\)O(2p,\(\gamma\))\(^{17}\)Ne, \(^{18}\)Ne(2p,\(\gamma\))\(^{20}\)Mg and \(^{38}\)Ca(2p,\(\gamma\))\(^{40}\)Ti reactions considered in Ref. [43], the latter can act as an efficient reaction link at conditions typical for X-ray bursts on neutron stars. A \(^{40}\)Ti \(\rightarrow\) p + p + \(^{38}\)Ca Coulomb dissociation experiment should be feasible. The decay with two protons is expected to be sequential rather than correlated (\(\alpha\)\(\alpha\)-emission). The relevant resonances are listed in Table XII of Ref. [43]. In Ref. [44] it is found that in X-ray bursts 2p-capture reactions accelerate the reaction flow into the \(Z \geq 36\) region considerably. In Table 1 of Ref. [44] nuclei on which 2p-capture reactions may occur, are listed; the final nuclei are \(^{68}\)Se, \(^{72}\)Kr, \(^{76}\)Sr, \(^{80}\)Zr, \(^{84}\)Mo, \(^{88}\)Ru, \(^{92}\)Pd and \(^{96}\)Cd (see also Fig. 8 of Ref. [38]). It is proposed to study the Coulomb dissociation of these nuclei in order to obtain more direct insight into the 2p-capture process.

5 Antihydrogen production and electromagnetic processes at relativistic heavy ion colliders

The process

\[ \gamma + \bar{p} \rightarrow \bar{H}^0 + e^- \]  

(10)
leads to antihydrogen \[ 10, 17 \]. The photons can come from the Coulomb field of a target nucleus, the antiprotons are available as a medium energy beam. Thus the produced $\bar{H}^o$ will have essentially the same velocity as the incoming $\bar{p}$ beam. This was realized at LEAR with antiprotons impinging on a Xe (Z=54) cluster target \[ 48 \]. In this way antihydrogen atoms were produced and detected for the first time. Presently, $\bar{H}^o$ atoms are produced at FERMILAB with essentially the same method. It remains to be seen whether further experiments (e.g. measuring the Lamb-shift of $\bar{H}^o$ \[ 46 \]) are possible with these fast neutral $\bar{H}^o$ beams.

A more accurate method will be the production of cold antihydrogen in traps. This will offer the possibility to use LASER spectroscopy and measure the spectrum of $\bar{H}^o$ with very high precision (e.g. the 1s-2s transition). This can be a significant test of the CPT-theorem.

A related process might be important in the future relativistic heavy ion colliders like RHIC at Brookhaven National Laboratory and LHC at CERN. The capture of electrons

$$Z + Z \rightarrow (Z + e^-) + e^+ + Z$$

leads to a change of the charge state of the circulating naked ions and therefore to a beam loss and luminosity decrease. The cross section for this process scales approximately with $Z^7$ and will be of the order of 100 b for heavy systems (like Au-Au (Z=79) or Pb-Pb (Z=82)). Another source of beam loss with cross sections of a similar order of magnitude is the excitation of the giant dipole resonance, with subsequent nucleon emission. The collision of equivalent photons can be used to study photon-photon collisions (“double Primakoff effect”). Up to now, this has mainly been done at $e^+e^-$ colliders. Due to the $Z^4$ factor in the cross section heavy ion colliders can be favourable. At RHIC one can explore the invariant mass range up to several GeV, and at LHC about 100 GeV. Unlike for $e^+e^-$ colliders there is a strong interaction background, which has to be taken care of. This is studied in the LoI for the proposed FELIX detector at LHC \[ 50 \]. Such $\gamma\gamma$ collisions lead to the production of lepton pairs ($l = e, \mu, \tau$), $C = +1$ mesons ($\pi^0, \eta, \eta_c, \eta_b, \ldots$), vector meson pairs, Higgs-bosons, etc. This subject would actually be another lecture and we wish to limit ourselves to these remarks. Further references can be found in \[ 50, 51 \].

6 Conclusions

Peripheral collision of medium and high energy nuclei (stable or radioactive) passing each other at distances beyond nuclear contact and thus dominated by electromagnetic interactions are important tools of nuclear physics research. The intense source of quasi-real (or equivalent) photons has opened a wide horizon of related problems and new experimental possibilities to investigate efficiently photo-interactions with nuclei (single- and multiphoton excitations and electromagnetic dissociation).

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